

Annual Report (Sept. 7, 1999 to Jan. 7, 2001) for NASA Contract NASW 99-029, "Energetic Ion Interactions with the Galilean Satellites"

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Most Significant Accomplishment

Major paper in press at Icarus on modeling of surface ice irradiation on Europa, Ganymede, and Callisto from energetic particle spectra measured by the Energetic Particle Detector on Galileo Orbiter.

1. OVERVIEW

1.1 Objectives

The principal research tasks of this investigation are specification of the energetic (keV to MeV) ion environments upstream of the four Galilean satellites along with data analysis and numerical modeling of observed ion interactions with the satellites. Differential flux spectra are being compiled for the most abundant ions (protons, oxygen, and sulfur) from measurements at 20 keV to 100 MeV total energy by the Energetic Particle Detector (EPD) experiment (Williams *et al.* 1992) and at higher ion energies by the Heavy Ion Counter (HIC) experiment (Garrard *et al.* 1992). Runge-Kutta and other numerical techniques are used to propagate test particles sampled from the measured upstream spectra to the satellite surface or spacecraft through the local magnetic and corotational electric field environment of each satellite. Modeling of spatial variations in directional flux anisotropies measured during each close flyby provides limits on atomic charge states for heavy (O, S) magnetospheric ions and on internal or induced magnetic fields of the satellites. Validation of models for magnetic and electric field configurations then allows computation of rates for ion implantation, sputtering, and energy deposition into the satellite surfaces for further modeling of observable chemical changes induced by irradiation. Our ongoing work on production of oxidants and other secondary species by ice irradiation on Europa's surface has significant applications, already acknowledged in current literature, to astrobiological evolution. Finally, the work will improve understanding of energetic ion sources and sinks at the satellite orbits for improved modeling of magnetospheric transport processes. The scope of the research effort mainly includes data from the primary Galileo mission (1995-1997) but may also include some later data where directly relevant (e.g., comparison of J0 and I27 data for Io) to the primary mission objectives. Funding for this contract also includes partial support for our related education and public outreach activity, "Interaction of Magnetospheric Particles Applied to Classroom Teaching (IMPACT)."

1.2 Investigation Team Members and Responsibilities

The list of participants remains as originally proposed. As Principal Investigator, I have overall responsibility while also working more specifically on modeling the directional anisotropy of the HIC and EPD ion fluxes during selected satellite flybys, initially for Io, and on calculations of irradiation parameters for applications to surface chemistry. Dr. Edwin V. Bell II, a funded Co-I from Raytheon ITSS at NASA GSFC, is supporting the effort on numerical modeling of ion trajectories near the satellites through adaption of related codes previously developed for his dissertation research at the University of Kansas (Bell and Armstrong, 1986; Bell, 1990). He is also developing Java versions of reduced versions of the trajectory codes in support of the IMPACT educational activity. Our other Raytheon Co-I, Dr. David R. Williams, is working exclusively on IMPACT with the collaborating teacher intern, Dr. Elizabeth A. Myhill at Marymount University, but has other support for this work through Raytheon's SSDOO Project at NASA GSFC (NASA contract NAS5-98156). Dr. Myhill is supporting IMPACT work at Raytheon through a consultant subcontract. Prof. Robert E. Johnson at the University of Virginia is supporting the work on irradiation effects as an unfunded Co-I. Dr. Neil Gehrels at NASA GSFC independently supports part of my work on HIC data analysis and modeling through the SSDOO Project and is participating as an unfunded Co-I in this investigation.

The other Co-I's not directly supported through the Raytheon contract include Dr. Christina Cohen of the California Institute of Technology (CIT) and Dr. Barry Mauk from the Applied

Physics Laboratory of Johns Hopkins University (APL / JHU). These Co-I's are respectively supporting the investigation through direct processing of energetic ion spectra at selected time intervals from the HIC and EPD experiments and through participation in data analysis and modeling. Dr. Mauk has already been funded through this investigation for two years via a separate contract at APL/JHU. Dr. Cohen did not require any funding for the first year of this investigation but will require start-up of a separate contract to Caltech for her proposed funding (see attachment with updated Caltech budget) during the second year.

1.3 Data Resources and Models

In the first year of work we have established working agreements for data exchange with our Co-I's and/or other collaborators on the Heavy Ion Counter (HIC), Energetic Particle Detector (EPD), and Galileo Magnetometer experiments. All relevant HIC data in record mode (highest time resolution of two seconds) from the primary and extended missions for Io and Europa flybys through orbit E15 have been processed into tabular form and merged with ancillary ephemeris, attitude, and magnetic field data at 1/3 second resolution as graciously provided by the magnetometer group of Prof. Margaret G. Kivelson at UCLA. In computation of magnetic pitch angles for the HIC sensor direction we have used both the measured magnetic field vectors and those from the magnetospheric model of Dr. Khurana at UCLA. For the initial work this past year on upstream particle spectra and irradiation modeling we have focused on EPD data from early mission flybys of Europa (E4), Ganymede (C2), and Callisto (C3). The EPD ion spectra for H, O, and S cover 20 keV to 100 MeV in total ion energy. Since much of the energy flux for satellite irradiation effects is carried by energetic electrons, we have also compiled electron spectra. We have extended the EPD electron coverage at 20 keV to 0.7 MeV with data from the JPL model of Divine and Garrett (1983); the model data overlap the EPD endpoint in energy, agreeing there surprisingly well, and extend up to 40 MeV.

For numerical modeling we have heavily modified the particle trajectory code of M. Shea and D. Smart, originally implemented for computations of cosmic ray cutoffs in the earth's magnetosphere, to compute ion trajectories in the Jovian magnetosphere within the vicinity of the Galilean satellites. To date this code has mainly been applied to modeling of ion interactions with Io and Ganymede. Some initial tests have been done on addition of an Alfvén wing subroutine from Khurana and Martin Volwerk at UCLA to include field components from current systems in the satellite ionospheres. Recently we have used an empirical dipole model for Io, in which the direction of the dipole field is reversed between the downstream and upstream hemispheres to represent depressed fields in the first case and compressed fields in the second; in these cases the 'dipole' approximates the effects of currents flowing in anti-jovian directions through the downstream and upstream ionospheric regions near the surface of Io. We have also acquired 3-D grids of magnetic field vector components and plasma flow velocities from Jon Linker of SAIC for his MHD code simulations of the first (J0) Io encounter. Usage of such pre-computed grids of the field data, either from the Linker or UCLA code outputs, will later allow us to speed up the particle trajectory computations while also using more realistic magnetic and plasma flow environments.

1.4 Publications and Presentations

A complete listing of investigation-related journal papers and conference presentations is given in Section 4. Meetings attended with contract support included the Fall 1999 AGU Meeting in San Francisco, the Io/HST Workshop at the University of Colorado, and the AAS

2000 Division of Planetary Sciences Meeting in Pasadena. We also include lists of other published papers and press releases citing published and other presented material arising directly from this investigation. A discussion of specific research highlights from the first contract year is given in Section 2.

1.5 Education and Public Outreach

Our IMPACT teacher intern, Dr. Myhill, is proceeding with development of an initial IMPACT curriculum at high school physics level as documented in an accompanying teacher's guide to be provided in Internet-accessible format. Since the overall contract funding, and consequently her sub-contract with Raytheon ITSS, did not commence until after summer 1999, we applied for and received a no-cost extension of the present contract until January 7, 2001 to allow her to complete the initial delivery of the IMPACT material, the final version being due by the end of the second contract year. Work is in progress by Dr. Ed Bell, our funded Raytheon ITSS Co-I's on an initial Java implementation of computer simulations for particle trajectories in magnetic fields in support of ongoing research and the IMPACT effort. Dr. Bell and co-authors (Bell *et al.*, 1999) previously made a initial report on IMPACT planning at the 1999 Spring AGU Meeting in Boston.

1.6 Work Plan for the Second Year

Work in the second year will complete the compilation of energetic particle spectra upstream of the four Galilean satellites from EPD and HIC measurements during the primary mission. This will require a continuing interaction with the responsible investigation members, Dr. Cohen at Caltech and Dr. Mauk at Applied Physics Laboratory, and implementation of procedures to merge the ion spectra from the two instruments. A prime focus at Raytheon ITSS will also be the improvement of existing particle trajectory routines to compute global distributions of irradiation parameters on the satellite surfaces for interpretation of remote sensing observations potentially related to irradiation effects. Effects of Ganymede's 'magnetospheric' magnetic field on latitudinal and longitudinal distributions of irradiation parameters are of particular interest. Ongoing work on modeling of HIC data for measured flux anisotropies near Io will be completed and submitted for publication. This work will also be extended to analysis of similar anisotropies observed during many Europa flybys of the primary and extended missions. The IMPACT curriculum materials will be finalized along with on-line demonstrations of charged particle motions in planetary and satellite magnetic fields under development by Raytheon staff.

Support for Dr. Cohen at Caltech in the second year should be provided via a separate new grant to Caltech from NASA. Note that Caltech did not request funding for the first year in our original proposal, so no contract has yet been issued to them by NASA. Separate first year and renewal grants have already been provided by NASA to Dr. Mauk at APL/JHU.

2. Research Highlights

2.1 HIC Results from Io

Heavy Ion Counter (HIC) and magnetometer field data were returned from three of the four Galileo Orbiter flybys of this satellite, data from the fourth (I25) being lost due to a spacecraft system anomaly likely induced by the intense magnetospheric radiation environment. In Figure 1 the spacecraft trajectories are shown for flybys J0 (Dec. 7, 1995), I24 (Oct. 11, 1999), and I27 (Feb. 22, 2000). For this report from the presented HIC results of Cooper (2000) and Cooper *et al.* (2000a) we use a satellite-centered coordinate system in which the +X axis is directed towards the center of Jupiter, +Y is in the upstream direction with respect to plasma corotation with the planetary magnetic field, and +Z is directed northward in the Jovian system. The J0 flyby was unique in crossing the corotational wake of Io while the two later flybys first approached Io on the upstream side and never entered the geometric wake thereafter. None of these passed through the polar cap region of the satellite, although the ill-fated I25 flyby on Nov. 26, 1999 was designed to do exactly that. Energetic Particle Detector (EPD) data reported by Mauk *et al.* (2000) indicate that the spacecraft may have passed through a local magnetic field line attached to the Io surface during the I27 pass.

In Figure 2 we present a complete overview of HIC and ancillary data from the J0 pass through the Io wake. The top panel shows the spacecraft altitude, the measured magnetic field magnitude (B), and the HIC count rate for heavy ions at energies above the single coincidence threshold energy of 2.4 MeV/nucleon for the LET-B sensor (Cohen *et al.*, 2000a). The deep variations in the count rate reflect strong variation in directional anisotropies of the ions as the spacecraft passed near Io and through the wake region.

These anisotropies are explicitly revealed in the middle panel of Figure 2 where the count rate is shown on a color scale (red is highest, purple is lowest) as a function of spacecraft spin angle and position along the X_{Io} axis. The spacecraft spin period is about twenty seconds. The spacecraft spins around an axis pointing approximately away from the direction of Earth, and the angle increases from 0° , where the spacecraft X_{sc} axis points downwards towards Ecliptic South, towards 90° where it is directed in the upstream direction during this Io encounter. The HIC sensors look towards and away from Io near closest approach at spin angles of about 45° and 225° , respectively; these directions are also approximately perpendicular to that of the local magnetic field lines along the spacecraft trajectory. The intensely red regions on the right side of this panel are centered on these perpendicular directions, as expected for energetic ions trapped in the Jovian magnetic field and preferentially accelerated at large magnetic pitch angles.

The large bit-outs at $\sim 90^\circ$ pitch angles in the magnetospheric ion distributions arise from absorption of the counted ions by the satellite surface. Within the depressed magnetic field of the Io wake region, ions at energies above the LET-B channel threshold have gyroradii of the order of the satellite radius, if the charge states of those ions are low, less than +4 for oxygen ions and less than +5 for sulfur. A depletion of count rate is then observed at some times (e.g., when $X_{Io} < -1.5$) when the HIC sensor is directed towards Io and but not when directed away from the surface. On closer approach to Io the ions become depleted when HIC looks both towards and away from Io as indicated by the large central absorption feature at all spin angles. The totality of the absorption features gives a distorted image of the shadow of Io as ‘observed’ with energetic ions measured by HIC.

In the lower panel of Figure 2 the results of ion trajectory calculations are overlaid on a corresponding contour plot of the measured HIC ion intensity. At 2/3-second intervals (resolution of the spacecraft attitude data) we numerically trace the ion trajectories back along the pointing direction of the HIC sensor; each dark point on the contour plot indicates a trajectory that would have been blocked by the Io surface. The ‘best-fit’ charge state for oxygen ions in this case is $Q = +2$ but we show the $Q = +3$ results for comparison with the I27 data discussed below. The predicted delay in depletion onset between pointing directions towards and away from Io on approach to the satellite are well matched by the distribution of points. In this case the magnetic field environment has been modeled by a superposition of the background magnetospheric field, as predicted by the model of Khurana (1997), and an internal dipole aligned with the Jovian field lines near Io so as to depress the total field magnitude in the wake region. The full absorption feature at all spin angles is not yet well modeled since the ion motions are followed backward in time only for a few gyroperiods. Also, presently we only follow ions coming in along the HIC sensor centerline. Some other ion trajectories might in fact have intersected the surface if followed for longer times, or if distributed over the full $\sim 25^\circ$ conical angle of the HIC aperture. These limitations will be removed in later work.

The same overview is given in Figure 3 for data from the I27 Io flyby during which the spacecraft approached Io from the upstream direction where the local magnetic field increased above ambient magnetospheric levels, likely due to effects of compression by the corotating magnetospheric plasma on this side of Io. For this flyby the spacecraft approached Io upstream from the $+X_{Io}$ direction (Figure 1) and initially encountered bidirectional absorption near closest approach to Io. The lack of unidirectional features here, like those in Figure 2, indicates relatively higher magnetic field magnitudes giving smaller ion gyroradii at similar charge states for the ions. As the spacecraft passes by Io into the downstream region, but not directly into the geometric wake, the outbound HIC and depletion model data do again indicate unidirectional absorption consistent with lower magnetic fields and larger gyroradii as inferred from the J0 pass across the wake. Note that in the computational model we reversed the polarity of our ‘empirical’ dipole for the upstream trajectories to match the higher magnetic field values. This reversal appears consistent with the inbound-outbound asymmetry in the magnetic field (top panel, Fig. 3), closest approach to Io being in the general region of the reversal longitude (180° in the X_{Io} - Y_{Io} system) on the anti-jovian side of the satellite.

The results of the HIC ion data and ion trajectory simulations from the two Io flybys considered here are then two-fold. First, heavy ion charge states must be low ($Q = +2$ to $+3$ for oxygen) to allow the large ion gyroradii inferred from the J0 results in the satellite wake region, irrespective of whether the wake magnetic field is depressed by an actual internal magnetic dipole or by satellite ionospheric currents producing similar effects as measured at the spacecraft and affecting motions of HIC ions. Second, a symmetric internal dipole, which would equally depress the fields both upstream and downstream in the absence of other (plasma, ionospheric) effects, cannot fit the upstream results from the I27 data unless it is hidden within other field components from large current systems not modeled here. The simpler interpretation is that such a dipole, if it even exists, is too weak to observably affect fields in the Io magnetic environment.

2.2 HIC Results from Europa

In Figure 4 the spacecraft trajectories are shown from the E4 to E15 Europa flybys, for which we have to date compiled HIC LET-B count rate data along with ancillary data for spacecraft

position, spin angle, and local magnetic field magnitude. In that the present investigation nominally covers only the primary mission data through orbit E11, we elect here to show only the E4 (Figure 5) and E11 (Figure 6) measurements from HIC in the same formats as in Figures 2 and 3, except that the bottom panels with computational results are not included. The trajectories in Figure 4 indicate that both of these flybys had closest approaches to Io in the wake region, although the measured magnetic fields in the upper panels show little indication of wake-associated depressions like that found during the J0 pass of Io. An interesting difference, however, is that the plane of the E15 trajectory intersects the northern pole of Europa, while that for E4 intersects the equatorial zone.

Both the E4 and E11 data from HIC do show indications of unidirectional ion absorption on approach to the satellite in a manner consistent with the expected spin angle phases of depletions by the satellite surface. Note that the approaches were respectively from the $+X_{Io}$ and $-X_{Io}$ sides for E4 and E11, and that depletions were first evident at spin angles near 225° for E4 and 45° for E11. The otherwise different appearances of the depletion structures probably arise from the more localized contact of gyrating ions with the northern polar region during E11 as compared to the more widespread contact with the equatorial zone during E4. These differences will be used to place even tighter constraints on ion and magnetic field parameters in future work.

2.3 Satellite Irradiation Effects

A major milestone of this investigation was achieved with acceptance in June of the lengthy paper by Cooper *et al.* (2000b) for publication in the planetary science journal *Icarus*. This paper presented a compilation of 20 keV to 100 MeV flux spectra for ions, and up to 40 MeV for electrons, from the respective E4 (Dec. 19, 1996), G2 (Sept. 6, 1996), and C3 (Nov. 4, 1996) flybys of Europa, Ganymede, and Callisto with the goal of utilizing these spectra to model effects of magnetospheric irradiation on the icy surfaces of these three satellites. The spectra compiled from EPD measurements for electrons, protons, and ions of oxygen and sulfur are shown in Figure 7. The JPL Jovian trapped radiation model of Divine and Garrett (1983) was used to extend the electron spectrum above 0.7 MeV, where the agreement between the measurement and the model is surprisingly good. In Figure 8 we show the results of model calculations using the spectra from Figure 7 to compute depth profiles in water ice for the rate of energy deposition by charged particle ionization. The vertical axis in Figure 8 shows the times in years needed to deposit 100 eV per molecule in each depth element. The depth bins were defined logarithmically to give equal weight to each decade of depth from sub-microns to millimeters. Note that micron depths can be totally processed by irradiation in times of several to tens of years, far shorter than the million to billion years time scales needed to produce resurfacing by geologic processes and impacts of large meteors. The curve labeled 'regolith depth' in Figure 8 gives the times needed to overturn the surface by impacts of small micrometeroids to the indicated depths. The faster rate of regolith growth means that observable production of irradiation products is correspondingly diluted by mixing of such material into the regolith. Thus present values (Carlson *et al.*, 1999a,b) on column densities of such products on Europa as hydrogen peroxide (H_2O_2) and sulfuric acid (H_2SO_4) may only be lower limits to the actual column abundances of such products distributed mostly below the depth limits $\sim 0.1 - 1$ mm of detection. Abundances of these products may have strong implications for astrobiological evolution in the putative sub-surface ocean of Europa.

It is also noted that one of our Co-I's, Bob Johnson, directly participated in the Carlson *et al.* publications based on remote sensing measurements of Europa's surface by the Near-Infrared Mapping Spectrometer (NIMS) on the Galileo Orbiter spacecraft. He has established a working collaboration with Bob Carlson of the NIMS team to aid in our future work as might be applicable to interpretation and modeling of the NIMS measurements. Other publications from the NIMS and other remote sensing teams have identified additional molecular species (e.g., O₂, O₃, CO₂) likely related to irradiation of surfaces on Ganymede and Callisto as well as on Europa. Many of these measurements were specifically addressed in terms of irradiation sources by the Cooper *et al.* (2000b) paper for Icarus.

In the case of Ganymede the magnetic moment on the internal dipole has been well determined by Galileo magnetometer measurements, so we have explicitly modeled irradiation dosages and other parameters for the polar region, essentially open to the magnetospheric particles, and for the equatorial zone, shielded from some particle types and energies by the magnetic field. The modeling results reported in the Icarus paper for these two regions are respectively shown in Figures 9 and 10 in the same format as used in Figure 8. While the incident measured fluxes of all particle types have free access to the polar region, the electrons and lower energy (< 10 MeV) protons are preferentially excluded from the magnetic equator of Ganymede. Interestingly, the high momentum/charge ratios (also called magnetic rigidity) of the heavy ions (e.g., O²⁺, S³⁺) allow easy access of these ions even through the magnetic field. This may explain why observed global distributions of some other irradiation products (e.g., SO₂) seem unrelated to the magnetic field zones. Global asymmetries in regolith growth rates (least on the upstream side of all the Galilean satellites) may also play a role, given that micrometeoroids should be unaffected by the Ganymede magnetic field.

3. REFERENCES

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4. CONTRACT PUBLICATIONS AND PRESENTATIONS

A wide variety of materials have been published, presented, or are in preparation or review from various members of our research collaboration. The following lists are cumulative and will be updated for subsequent reports focusing on different specific areas. Underlined names are for lead authors and co-authors who are members of our investigation team.

4.1 Journal Articles

- Carlson, R. W., M. S. Anderson, R. E. Johnson, W. D. Smythe, A. R. Hendrix, C. A. Barth, L. A. Soderblom, G. B. Hansen, T. B. McCord, J. B. Dalton, R. N. Clark, J. H. Shirley, A. C. Campo, and D. L. Matson, Hydrogen peroxide on the surface of Europa, *Science* **283**, 2062-2064, 1999.
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4.2 Conference Presentations

- Bell, E. V. II, D. R. Williams, E. Myhill, and J. F. Cooper, Interaction of Magnetospheric Particles Applied to Classroom Teaching (IMPACT): Educational Outreach, *Eos Trans. AGU*, **80(17)**, 1999 Spring Meet. Suppl., S270, 1999. {contributed poster, Bell}
- Cooper, J. F., Galileo HIC and EPD measurements for direct interactions of energetic ions with Io, talk presented at Galileo/HST Io Workshop, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Feb. 28-29, 2000a. {contributed talk}
- Cooper, J. F., The Jovian hot plasma interactions with the surfaces of the icy satellites, invited talk at 33rd COSPAR Scientific Assembly, Warsaw, Poland, July 16-23, 2000b. {invited}
- Cooper, J. F., and E. V. Bell II, Energy cutoffs for penetration of Jovian energetic particles to the surface of Ganymede through the satellite's magnetic field environment, *Eos Trans. AGU*, **80(17)**, 1999 Spring Meet. Suppl., S301, 1999. {contributed poster, Bell}
- Cooper, J. F., E. R. Christian, R. E. Johnson, and H. B. Garrett, Heliospheric interactions with interplanetary ices in the solar system, contributed poster presented at 34th ESLAB Symposium, the 3D Heliosphere at Solar Maximum, ESTEC, Noordwijk, the Netherlands, Oct. 3-6, 2000.
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- Cooper, J. F., R. E. Johnson, and V. I. Shematovich, Production of Europa's oxidants by magnetospheric particle and solar UV irradiation, abstract submitted for contributed poster at Fall 2000 AGU Meeting, San Francisco, CA, Dec. 15-19, 2000.
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- Johnson, R. E., Energetic ion sputtering of Europa's surface: loss of Na, presented at 31st Annual Meeting for the Division of Planetary Sciences AAS, Padova (Padua), Italy, Oct. 10-15, 1999. {contributed talk}
- Johnson, R. E., Exospheres and planetary escape, talk presented at Comparative Aeronomy in the Solar System, Yosemite National Park, Yosemite, California, Feb. 8-11, 2000. {contributed}
- Johnson, R. E., J. F. Cooper, R. W. Carlson, and M. C. Wong, Sputtering of the Icy Satellites, *Eos Trans. AGU*, **80(46)**, 1999 Fall Meet. Suppl., F600, 1999. {invited talk, Cooper}

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- Williams, D. J., and B. H. Mauk, Energetic particles at and near Io, *Eos Trans. AGU*, **80(46)**, 1999 Fall Meet. Suppl., F638, 1999. {invited talk, Mauk}

4.3 Selected Literature Citations

The following works cite relevant publications from the present investigation as compiled in the Web of Science Citation Database of the Institute for Scientific Information (ISI):

- Baragiola, R. A., C. L. Atteberry, and D. A. Bahr, Reply, *J. Geophys. Res.* **104**, 14183-14187, 1999. {cites Johnson 1999a}
- Carlson, R. W., M. S. Anderson, R. E. Johnson, W. D. Smythe, A. R. Hendrix, C. A. Barth, L. A. Soderblom, G. B. Hansen, T. B. McCord, J. B. Dalton, R. N. Clark, J. H. Shirley, A. C. Campo, and D. L. Matson, Hydrogen peroxide on the surface of Europa, *Science* **283**, 2062-2064, 1999a. {cites early version of Cooper *et al.* 2000}.
- Carlson, R. W., R. E. Johnson, and M. S. Anderson, Sulfuric acid on Europa and the radiolytic sulfur cycle, *Science* **286**, 97-99, 1999b. {cites Carlson *et al.* 1999a, early version of Cooper *et al.* 2000}.
- Chyba, C. F., Energy for microbial life on Europa, *Nature* **403**, 381-382, 2000. {cites Carlson *et al.* 1999a and Delitsky and Lane 1998 on material from early version of Cooper *et al.* 2000}
- Collins, G. C., J. W. Head, R. T. Pappalardo, and N. A. Spaun, Evaluation of models for the formation of chaotic terrain on Europa, *J. Geophys. Res.* **105**, 1709-1716, 2000. {cited Carlson *et al.* 1999b}
- Delitsky, M. L., and A. L. Lane, Ice chemistry on the Galilean satellites, *J. Geophys. Res.* **103(E13)**, 31391-31403, 1998. {cites early version of Cooper *et al.* 2000}.
- Gaidos, E. J., K. H. Nealson, and J. L. Kirschvink, Biogeochemistry - Life in ice-covered oceans, *Science* **284**, 1631-1633, 1999. {cites Carlson *et al.*, 1999a}
- Hudson, R. L., and M. H. Moore, Laboratory studies of the formation of methanol and other organic molecules by water + carbon monoxide radiolysis: relevance to comets, icy satellites, and interstellar ices, *Icarus* **140**, 451-461, 1999. {cites early version of Cooper *et al.* 2000}.
- Johnson, R. E., Sodium at Europa, *Icarus* **143**, 429-433, 2000. {cites Cooper *et al.* 2000, Carlson *et al.* 1999a}
- Khriachtchev, L., M. Pettersson, S. Jolkkonen, S. Pehkonen, and M. Rasanen, Photochemistry of hydrogen peroxide in Kr and Xe matrixes, *J. Chem. Phys.* **112**, 2187-2194, 2000. {cites Carlson *et al.* 1999a}
- Moore, M. H., and R. L. Hudson, IR detection of H₂O at 80 K in ion-irradiated laboratory ices relevant to Europa, *Icarus* **145**, 282-288, 2000. {cites Carlson *et al.* 1999a}
- Showman, A. P., and R. Malhotra, The Galilean satellites, *Science* **286**, 77-84, 1999. {cites Johnson 1999a, Carlson *et al.* 1999a,b}
- Vincent, W. F., Antarctic biogeochemistry - Icy life on a hidden lake, *Science* **286**, 2094-2095, 1999. {cites Carlson *et al.* 1999a}
- Vincent, W. R., Life in Lake Vostok, *Recherche* **329**, 14-16, 2000. {cites Carlson *et al.* 1999a}

4.4 Related Press Releases

Co-I Robert E. Johnson worked with his collaborator, Dr. Robert W. Carlson of the Jet Propulsion Laboratory, on analyses related to this investigation which led to the following two press releases. The published works (Carlson *et al.*, 1999a,b) cited irradiation parameters computed in Cooper *et al.* (1999).

"NASA's Galileo Spacecraft Finds 'Bottle Blonde' Chemical on Europa". Galileo Project, March 25, 1999. Quotes from R. W. Carlson. {based on Carlson *et al.* 1999a}

"Battery Acid Chemical Found on Jupiter's Moon Europa", Galileo Project, Sept. 30, 1999. Quotes from R. W. Carlson and R. E. Johnson. {based on Carlson *et al.* 1999b}

The following release anticipates our work submitted to Icarus in Cooper *et al.* (2000), in reference to irradiation as an astrobiological energy source for Europa, and the quoted work of Chyba (2000) indirectly refers to Europa energy fluxes in an early version of Cooper *et al.* (2000) {originally submitted to Science in Fall 1998} via citations of Delitsky and Lane (1998) and Carlson *et al.* (1999a).

"New findings support prospect of life on Jupiter's moon Europa", Mark Schwartz, Stanford University News Service, Jan. 26, 2000. Quotes from Chyba (2000) article in Nature.

FIGURE CAPTIONS

Figure 1. Galileo Orbiter spacecraft trajectories in Io-centered coordinates from the J0 (Dec. 7, 1995), I24 (Oct. 11, 1999), and I27 (Feb. 22, 2000) encounters. Upper plot: equatorial projections in the X_{I_0} - Y_{I_0} plane. The $+X_{I_0}$ axis is directed towards Jupiter and that for $+Y_{I_0}$ is in the upstream direction with respect to magnetospheric plasma corotation. Lower plot: meridional projections of the same trajectories into the X_{I_0} - Z_{I_0} plane. (Sect. 2.1)

Figure 2. Overview of measured HIC LET-B (singles mode with threshold energy of 2.4 MeV/amu for oxygen ions) count rates, magnetic field magnitude, and ion trajectory model results, for the J0 (Fig. 1) encounter with Io. Upper panel: line plot of LET-B count rate, magnetic field magnitude (M. G. Kivelson *et al.*, priv. comm.), and spacecraft altitude. Middle panel: Color coded map of LET-B count rate versus X_{I_0} position and Inertial Rotor System (IRC) spin angle of the spacecraft. The HIC sensor points perpendicular to the local magnetic field vector at spin angles of about 45° and 225° where the background magnetospheric ions have highest (e.g., vertical centers of red regions on right side of the panel) directional intensity. Bottom panel: Contour plot of LET-B count rates, using the same color scale and coordinates as in the middle panel, and for incident 2.4-MeV/amu O^{3+} trajectories (dark points) blocked by the Io surface for the longitudinally asymmetric dipole model. (Sect. 2.1)

Figure 3. Overview of measured HIC LET-B (double coincidence mode with threshold energy of 4.0 MeV/amu for oxygen ions) count rates, magnetic field magnitude, spacecraft altitude, and ion (4.0 MeV/amu O^{3+}) trajectory model results, for the I27 (Fig. 1) encounter with Io. The plotted data are in the same formats as described in the Fig. 2 caption. (Sect. 2.1)

Figure 4. Equatorial (upper) and meridional (lower) projections (as in Fig. 1) of Galileo Orbiter spacecraft trajectories in Europa-centered coordinates (same as in Fig. 1) from the E4 (Dec. 19, 1996), E11 (Nov. 6, 1997), E12 (Dec. 16, 1997), E14 (March 29, 1998), and E15 (May 31, 1998) encounters with Europa (Sect. 2.2).

Figure 5. Overview of measured HIC LET-B (double coincidence mode with threshold energy of 4.0 MeV/amu for oxygen ions) count rates, magnetic field magnitude, and spacecraft altitude for the E4 (Fig. 4) encounter with Europa. The plotted data are in the same formats as described in the Fig. 2 caption, except that the bottom panel of that figure is not included. (Sect. 2.2)

Figure 6. Overview (same format as Fig. 5) of measured HIC LET-B (double coincidence mode with threshold energy of 4.0 MeV/amu for oxygen ions) count rates, magnetic field magnitude, and spacecraft altitude for the E11 (Fig. 4) encounter with Europa. (Sect. 2.2)

Figure 7. Particle flux spectra from EPD measurements by Cooper *et al.* (2000) of the magnetospheric environment of Europa during the Galileo Orbiter's E4 encounter as functions of total particle energy for one 20-sec interval chosen to represent the upstream environment. The electron spectra are shown both from EPD at 20 – 700 keV and from the model spectrum (DG-83) of Divine and Garrett (1983) extending up to 40 MeV. The EPD response range for H, O,

and S ions is 20 keV to 100 MeV. No charge state measurement is made by EPD for O and S ions. (Sect. 2.3)

Figure 8. Time scales in years for accumulation of $100\text{-eV}\cdot(16\text{-amu})^{-1}$ volume dosage, a benchmark value for significant chemical change, as functions of vertical depth at unit water ice density on the globally-averaged surface of Europa. The depth profiles are shown for the total dosages and for individual contributions from flux spectra (c.f., Fig. 7) of electrons and of the ions H^+ , O^{n+} , and S^{n+} . The time scale versus depth for growth of the meteoritic impact regolith is also shown from the model of Cooper *et al.* (2000b). (Sect. 2.3)

Figure 9. Depth profiles for total and individual dosage time scales (c.f., Fig. 8) of electrons and ions incident on the unshielded polar surface of Ganymede (Cooper *et al.*, 2000b). (Sect. 2.3)

Figure 10. Depth profiles for total and individual dosage time scales (c.f., Fig. 8) of ions incident on the magnetically shielded equatorial surface of Ganymede (Cooper *et al.*, 2000b). The assumed charge states for heavy ions are O^{2+} and S^{3+} . The shielding model excludes electrons at 20 keV to 140 MeV from reaching the surface, so no electron profile is shown. The proton curve is initially horizontal since the magnetic shielding deflects protons at energies below several MeV and none of these protons stop at small depths. (Sect. 2.3)

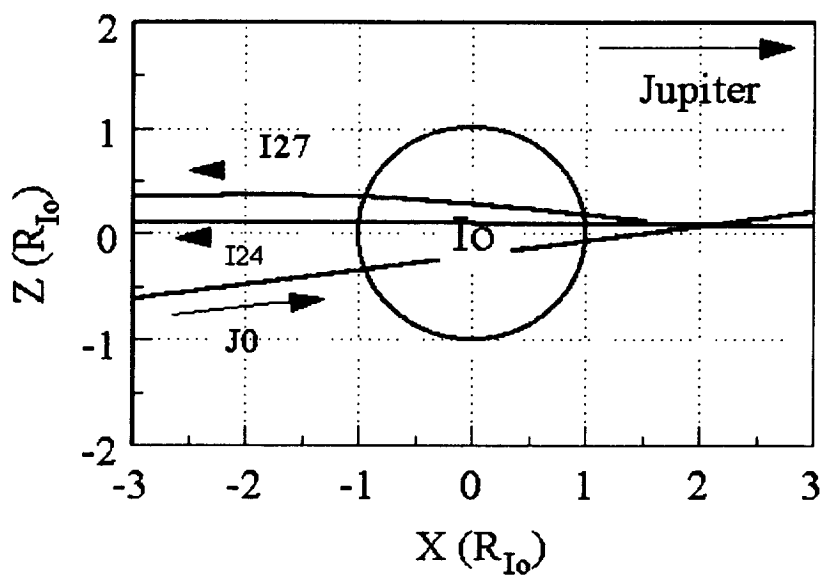
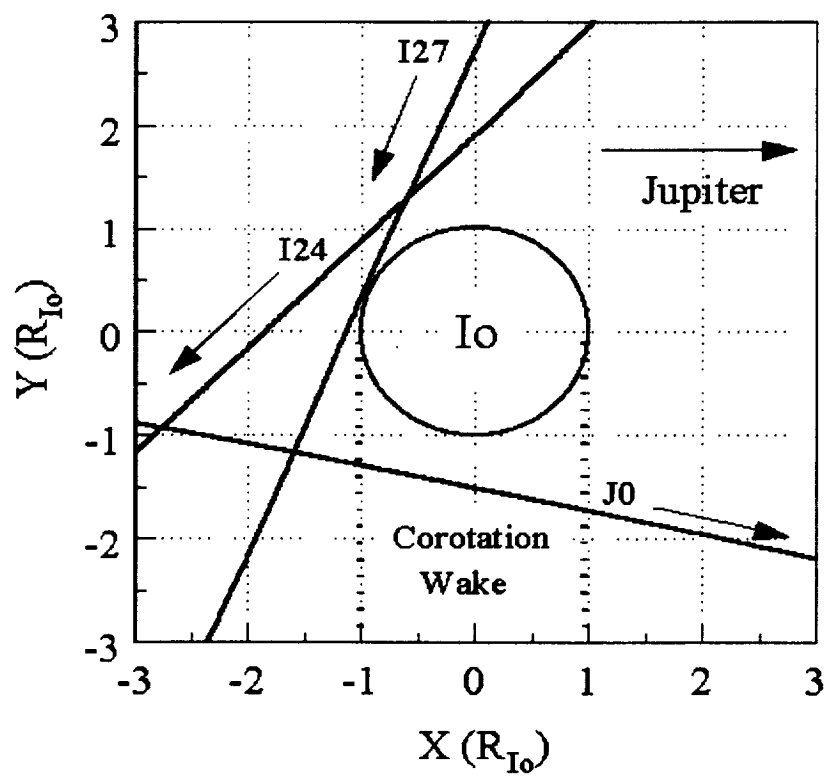


Figure 1

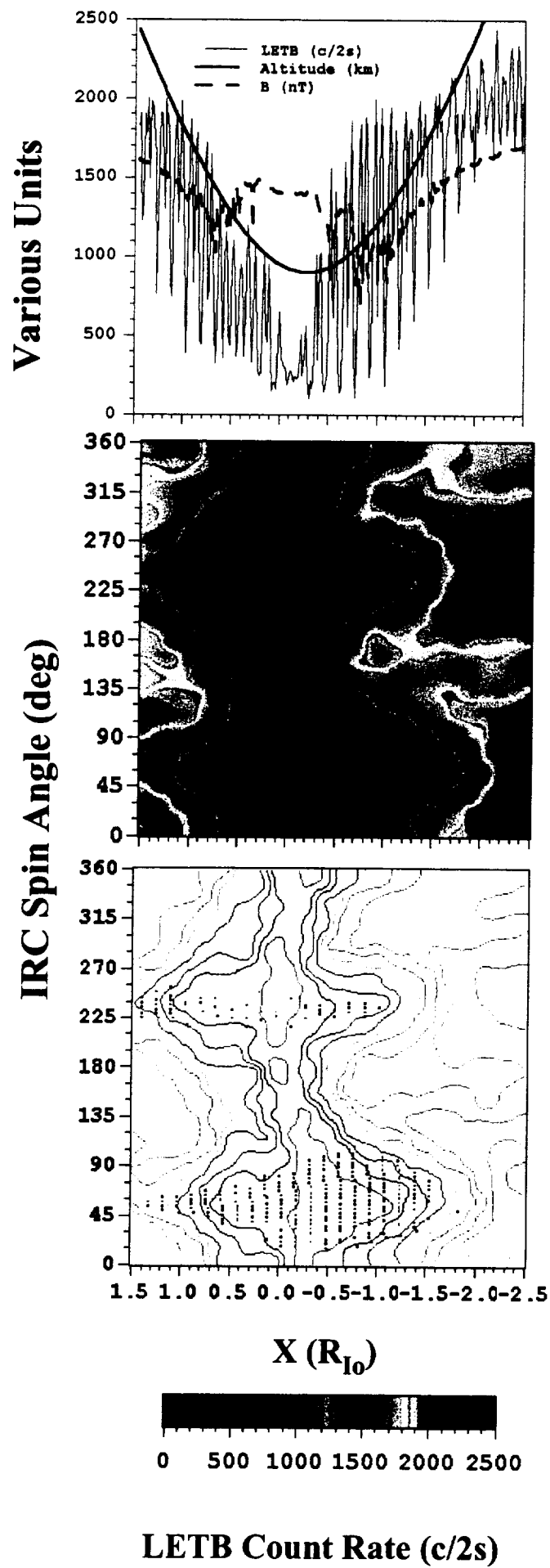


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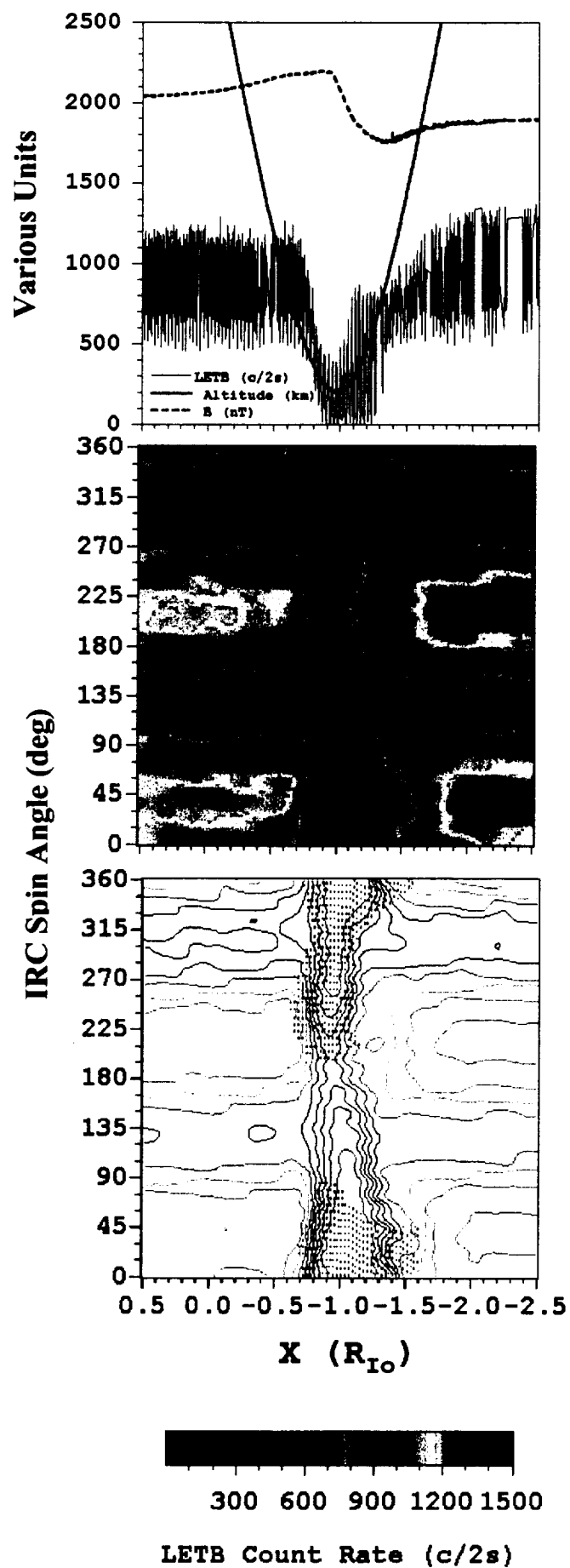


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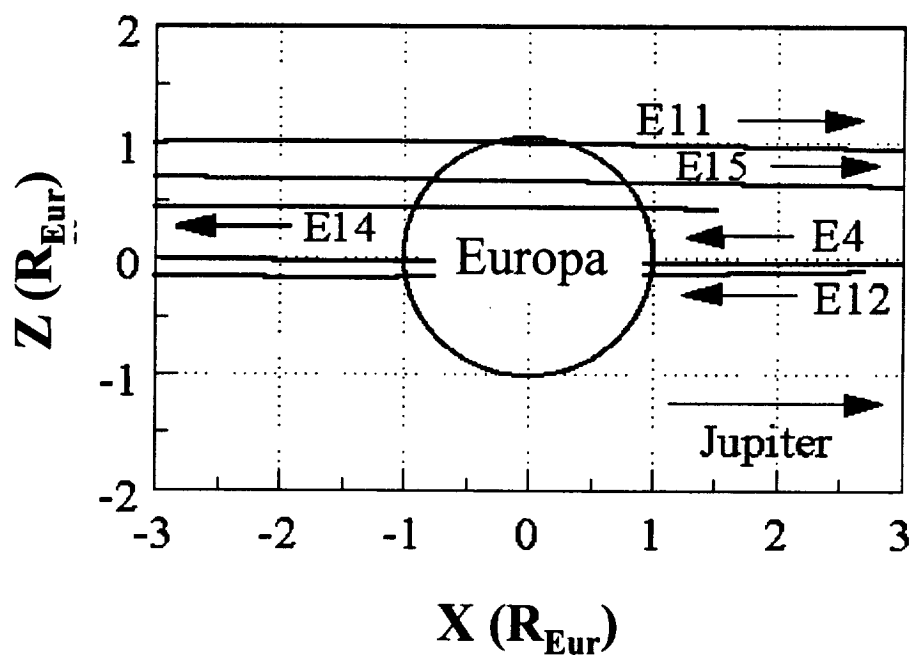
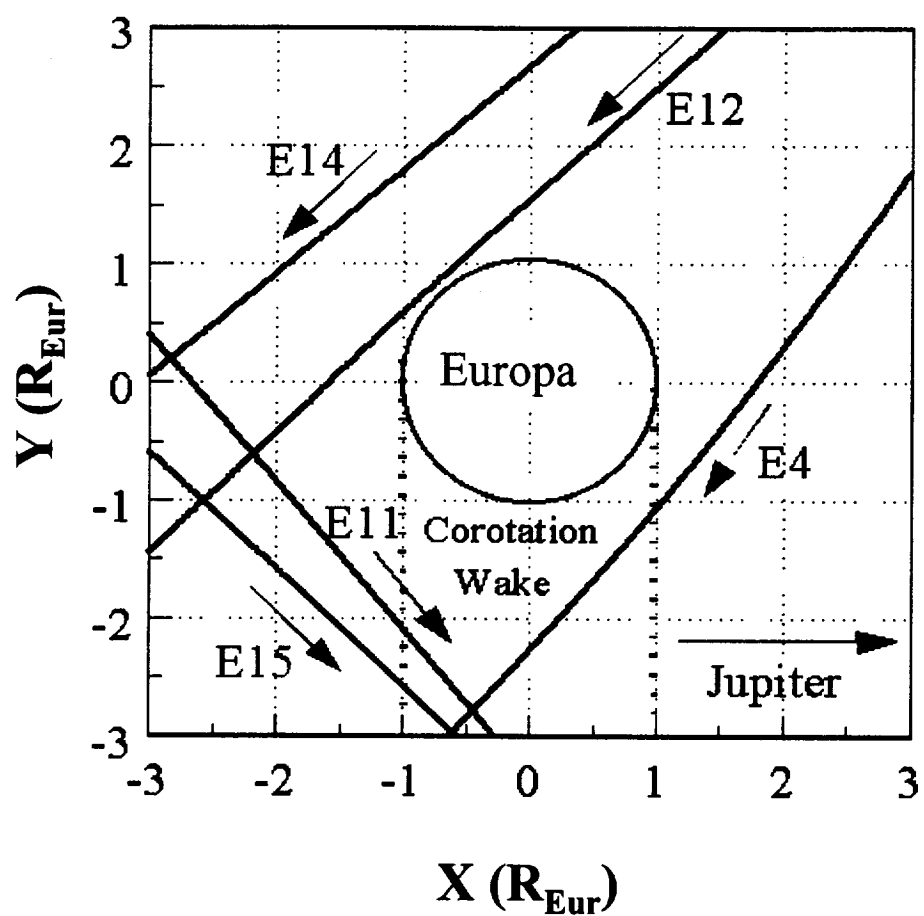


Figure 4

E4 Europa Flyby - Dec. 19, 1996

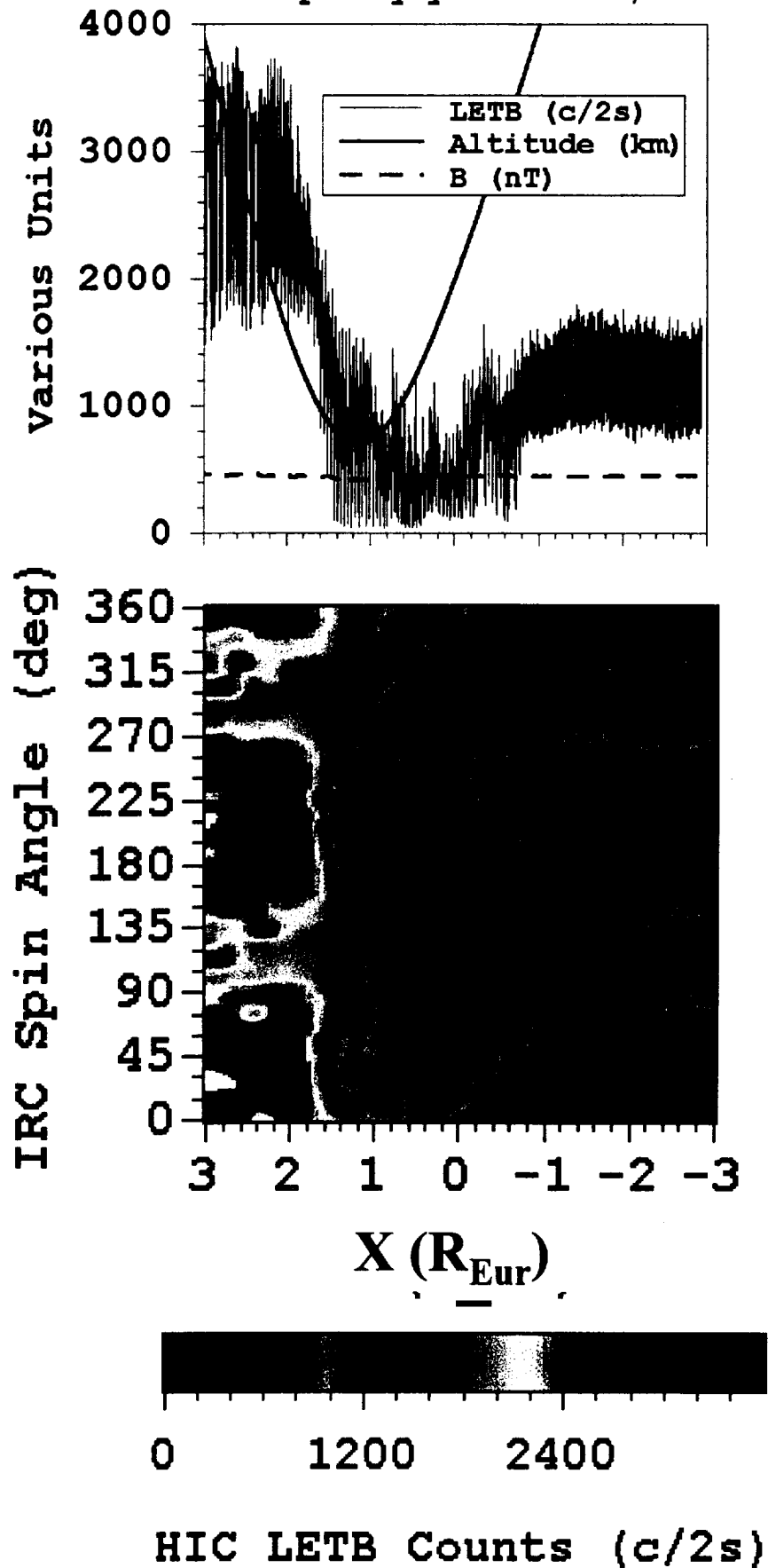


Figure 5

E11 Europa Flyby - Nov. 6, 1997

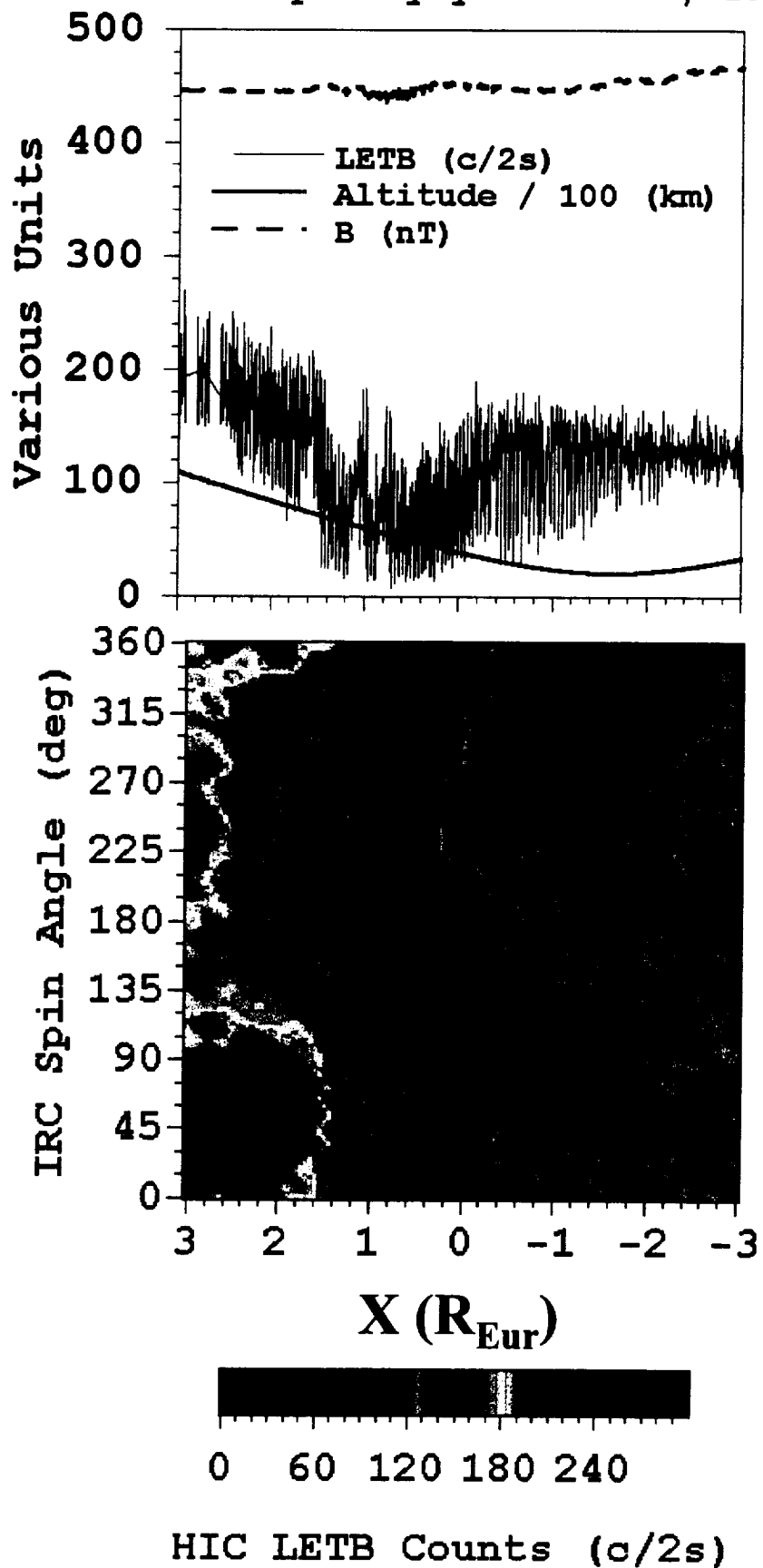


Figure 6

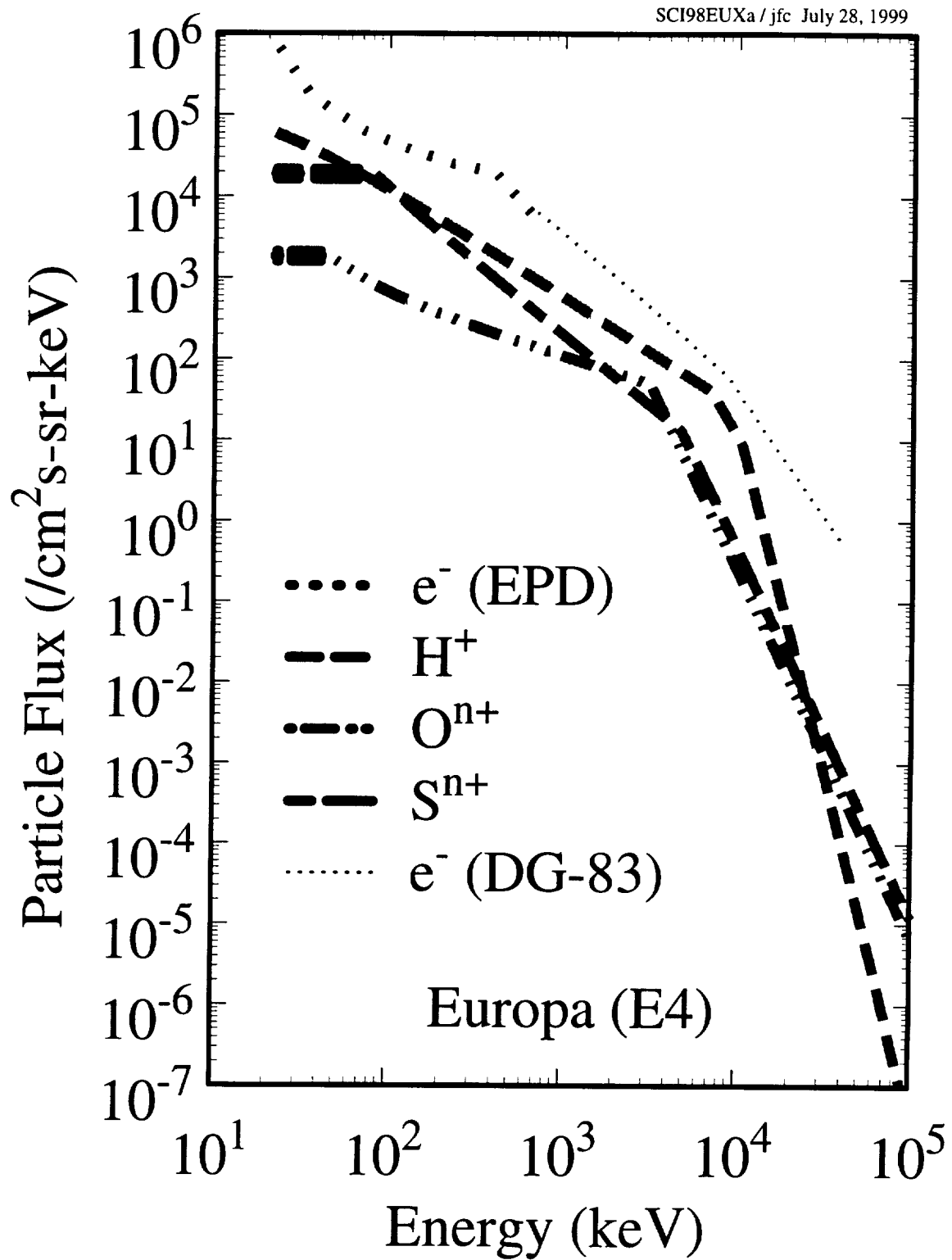


Figure 7

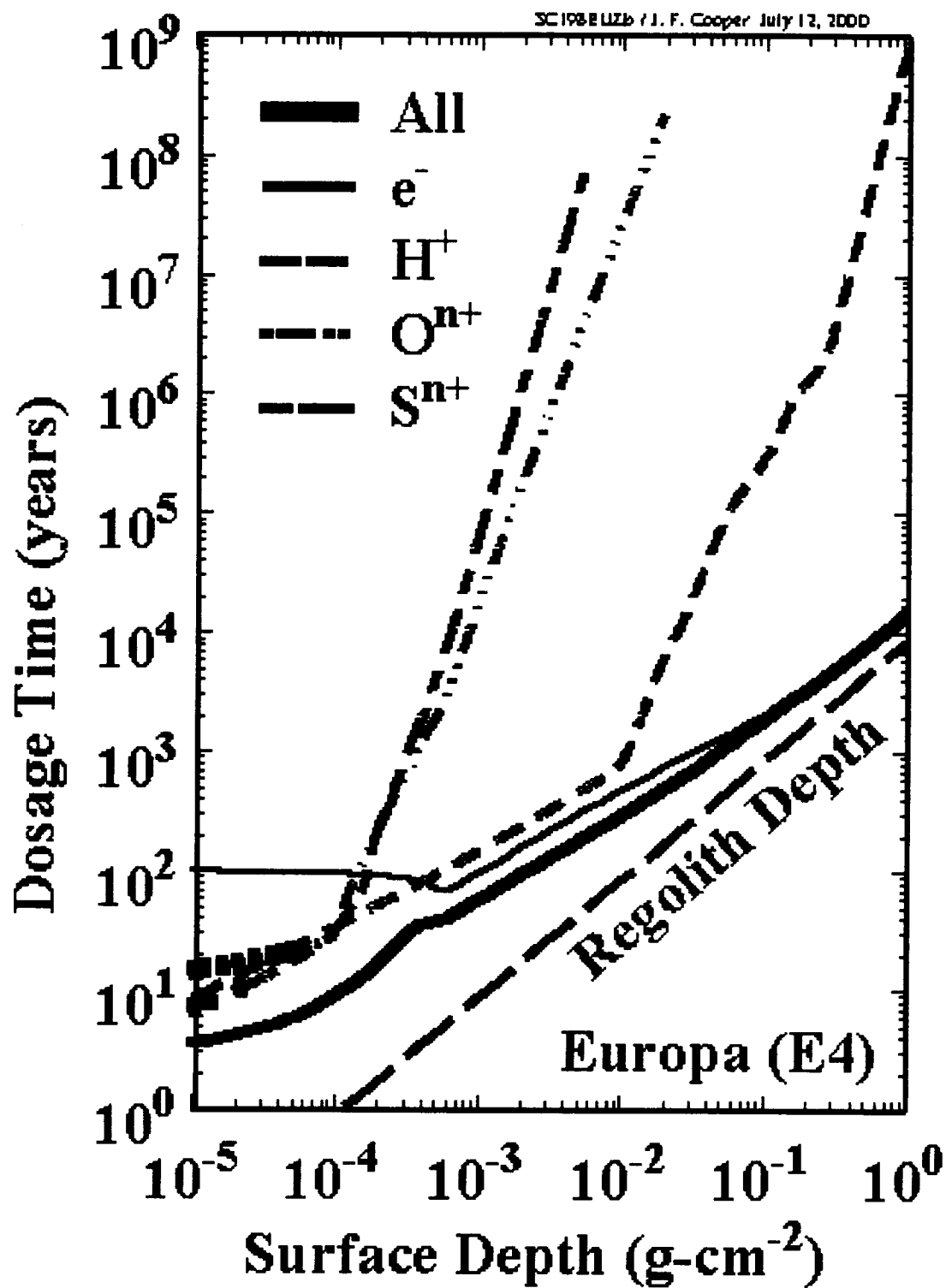


Figure 8

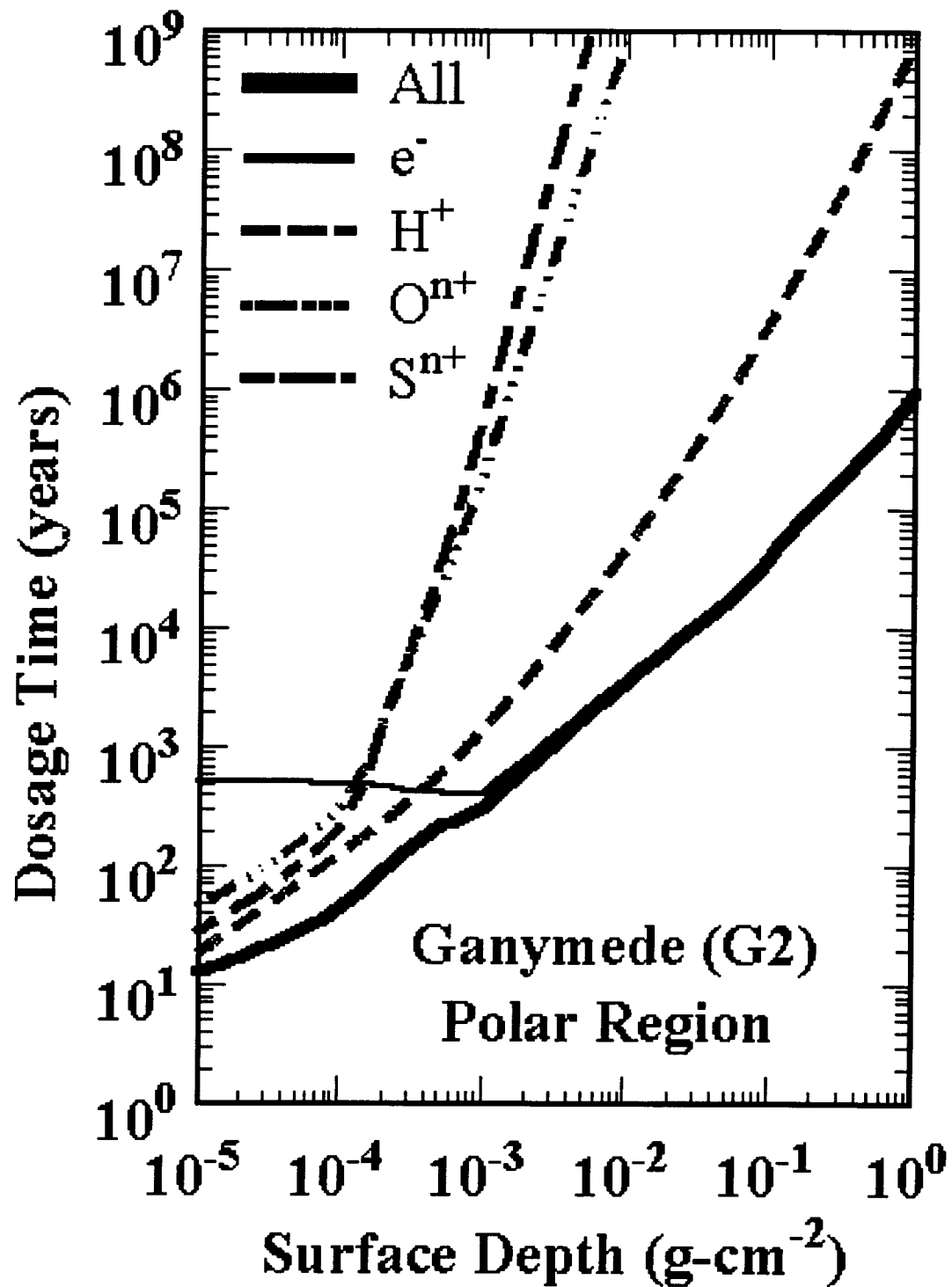


Figure 9

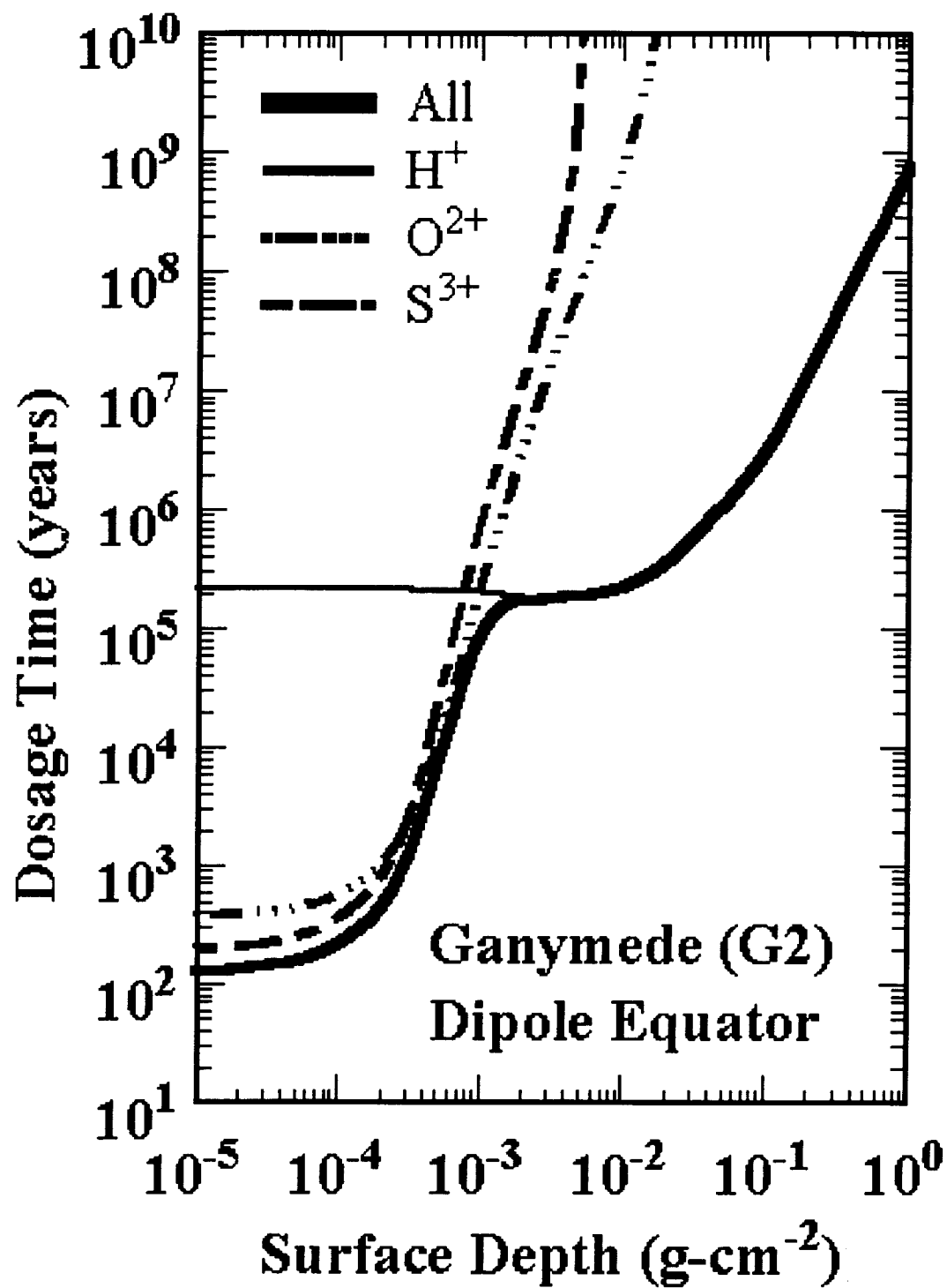


Figure 10